Error and the Nature of Science

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articlehighlights

Understanding the nature of science, especially how scientists err, is an essential tool for

- *assessing the reliability and scope of scientific claims*
- *perceiving the scope of these claims*
- *making personal and public decisions*

4

How science works is the key to understanding its concepts.

Scientific information abounds. New findings emerge daily. Imagine a study linking vaccinations to child autism: Should you believe it? Some government leader downplays the effects of global warming. Another claims that some hazardous waste material has been safely processed. The media report a study that cell phones may damage the brain. Science permeates choices in our lives, both public and private. No one can be expert in everything. The challenge, then—especially important for educators to appreciate—is learning how to deal with the information. Basic scientific concepts provide a framework. But one must also know about science—how research is pursued, how conclusions are justified, even how scientists may sometimes err or be shaped by cultural biases. This deeper understanding of the nature of science may help us assess the reliability of claims.

Profiling the Nature of Science

What features of the nature of the science are most important to know? Recent consensus highlights the following:

Observation comes from

- Scientists think critically about claims. Empirical evidence is their

ultimate standard.

angles.

- Scientists use a variety of methods: hypothesis, for instance, as well as analogy and induction. Some collect observations; others creatively recognize patterns in data. Imagination, logical reasoning, chance, and interdisciplinary thinking can all be important.

Scientists back their findings with multiple lines of evidence.

- Observation is sometimes enhanced by quantitative measurement, by comparison—especially with controls that isolate the effect of individual variables or help distinguish correlation from causation—and by graphical representation and statistical analysis summarizing patterns in the data and the chances for error.

- Data does not speak for itself. Rather, scientists interpret findings, and sometimes those interpretations are biased by theoretical or cultural perspectives.

- Scientific claims vary in their level of certainty. No method guarantees answers or absolute certainty, yet multiple lines of evidence help reinforce many claims. Even important problems may remain unresolved. In some cases, scientists may justifiably disagree.

Science deals with facts, not values.

- Science is a human enterprise. Some scientists are motivated by curiosity or a passion to solve problems, others by profit or ambition. Some collaborate; others compete.

- Knowledge develops historically. Sometimes concepts change dramatically.

- Science resolves only problems of fact, not values. Nonetheless, the practice of science and its results have moral dimensions.

- Science generally aims to map and explain the world. Technology differs in that it aims to adapt that understanding of the world.

Many features of the nature of science are expressed in terms of ideals, or aims. These are understood as rules that typically

Some

rooted in unsound principles.

support the growth of knowledge and its reliability. We should recognize, of course, that the actual practice of science does not always meet its ideal. For example, no one would endorse fraudulent scientific reports, but they occur occasionally. Similarly, we may hope to eliminate theoretical preconceptions that adversely affect our thinking. But human minds are very difficult to train on this score. Even so, sometimes theoretical commitments help motivate researchers or guide them in disregarding exceptions. For example, the widely held belief in a biblical flood guided geologists in the 1800s to study and catalog large rocks supposedly moved by the flood waters. Only later were others able to interpret them as glacial erratics. At the time, who would have been able to imagine huge rivers of ice pushing such boulders hundreds of miles from their bedrock? Yet once the geography of the erratics was known, it was easier to develop the concept of glaciers.

Tentativeness and Error

Can science be fallible and still be reliable?

Perhaps the most central feature of the nature of science involves scientific authority. We may be reminded that scientific claims are tentative or fallible. Reconciling these with other claims that science offers a reliable basis for action, however, can be problematic. We need a complete account of scientific error.

The gap caused by uncertainty and fallibility can offer a powerful persuasive wedge for political ideologues. Here are some examples:

Some people with agendas use its fallibility to undermine science.

- Creationists allege that evolution is “just a theory” and try to use the ideal of skepticism to insert their own empirically ill-founded ideas under the authoritative mantle of science.[1] (See first “learn more” link at end of article.)
- Others with economic interests have appealed to the incompleteness of science to argue that concerns about global warming and climate change are premature, despite growing scientific consensus.[2] (See first “learn more” link.) Such cases underscore the need for skills in assessing the context of and potential for error in science. Whether we regard claims about the safety of cell phones or high-voltage power lines, say, as true or

mistaken has wide implications.

While science can inform our lives, it can also err—with important social outcomes—as documented in some dramatic historical cases:

Others use racial bias in their scientific claims.

- Early in the 1900s scientists disagreed about the cause of pellagra, a prominent disease in rural southern America. Some contended it was a dietary deficiency, others said it was caused by a germ. Each theory led to a different course of public action. An independent commission was established to resolve the debate scientifically. Its head was Charles Davenport, director of the prestigious Cold Spring Harbor Laboratory.[3] Ultimately, the commission concluded that pellagra was, instead, genetic. In retrospect, we can see Davenport's biases. He was a racist and eugenicist, who saw the problem of the poor as their own shortcomings, not caused by social conditions. The "scientific" conclusion was wrong, yet it remained the basis for policy for many years. Later, Joseph Goldberger identified pellagra as a vitamin deficiency. Davenport's evidence seemed to support his theory because persons in the same family tended to share the same impoverished diet.

Errors in scientific claims can remain for decades.

- Davenport also exercised great influence in conceiving intelligence (as measured by IQ) as hereditary. Social implications included immigration and eugenic social control of reproductive rights. Should "feeble-minded" persons be prevented from having children, based on the scientific claim that they would only produce more "feeble minded" to burden society? Were individuals from certain geographical regions or races inherently inferior mentally, such that the government should limit admitting them into the country? Davenport studied numerous families and presented his findings in terms of genetic pedigrees. He persuaded many people to believe that low intelligence was genetic, not a product of an environment and poor education shared by successive generations of the same family. Immigration quotas and sterilization legislation followed from Davenport's and others' "scientific" claims and remained for decades.

These two cases of historical error underscore the social importance of understanding the potential for scientific error. They also provide clues about how to analyze scientific claims for such error. A full understanding of science thus includes understanding how it can err, and how such errors are themselves discovered and remedied.

Real science consists of a system of checks and balances.

Errors in science (that is, real science, not idealized science) vary considerably. Some may be relatively minor, such as failing to follow an experimental protocol properly, observing a small sample (unrepresentative of the whole), or overlooking a relevant control. Scientists generally learn how to reduce such errors during their apprenticeship in a lab. But the social framework of science also provides an important safeguard. A community of scientists, when it reflects contrasting perspectives, functions as an extended system of checks and balances. Importantly, not everything that is published becomes accepted fact!

Errors may be easy or hard to find and correct.

Other errors are deeper and harder to find or correct. Like those involving Davenport, they may be disguised in common cultural assumptions. Those who use scientific conclusions, as much as the scientists themselves, must be alert to such possible errors. One important critical tool, then, is knowing the spectrum of error types. Here is one framework for classifying and thinking about such error types, ranging from small- to large-scale effects:

Material

- improper materials (impure sample, contaminated culture)
- improper procedure (wrong experimental protocol, poor technical skill)
- phenomenon influenced by observer
- two different phenomena conflated due to lack of experimental distinction

Observational

- insufficient controls (causes or effects misplaced)
- incomplete understanding of instrument or how method of observation works

- perceptual bias ("theory-laden" observation, need for double-blind study)
- small, unrepresentative sample

Conceptual

- reasoning error (computational, logical fallacy, mistaking correlation for causation)
- mistaken assumptions or background information
- overgeneralization (unjustified scope of explanation)
- lack of alternative explanations (limited creativity) *psychological confirmation bias

Social

- communication failures (obscure publication, translation hurdles)
- fraud, faulty peer review, and other mistaken judgments of credibility
- sociocultural cognitive biases (gender, ethnicity, economic class, etc.)
- poor science education, poor science journalism

The remedy for tentativeness in science is active analysis of potential errors, guided by an awareness of error types. Analysis may qualify the scope or certainty of conclusions and guide policy accordingly.

Teaching Strategies

One solution is to talk about the nature of science.

Teaching nature of science (and error, in particular) requires a shift in emphasis. No amount of scientific content alone will ever be enough to develop full scientific literacy. Nature of science lessons must be inserted in the standard curriculum and regularly reinforced to encourage habits of mind. Several strategies may help:

Laboratory exercises and active reflection

The lab is

Many ideas about the nature of science are implicit in laboratory

exercises, long a part of science education. However, teachers deepen such lessons by making them explicit. In particular, active student reflection and interactive discussion help. Personal investigation offers a strong occasion for learning about the relevance of empirical data, to assess the need for controls, and to avoid making hasty conclusions about causes based only on correlation.

to learn about the nature of science.

Black-box exercises or mock-forensic activities (see "get involved" links at end of article) can also highlight (with some fun!) model building, model testing, interpretation of evidence, and model revision—and how each contributes to the blind, trial-and-error process of investigation.

Historical and current cases studies

Deeper lessons come through studying real scientists at work. Great discoveries of the past offer a great opportunity to dissect the process of science.4 Students may even be challenged with the questions or data of famous scientists, to appreciate science-in-the-making themselves. History is especially important for exhibiting the social and cultural contexts of science and for seeing how mistakes are later resolved.

Historical case studies present another opportunity.

Current events also offer great occasions for learning. For example, just as I write this, the news media is reporting on a 1998 study that linked childhood vaccinations with autism. The study used a small sample (12 children) and relied substantially on parents' memories. It has been widely discredited. Now, disclosure of a conflict of interest for the lead author has led to a formal retraction of the original paper. The case is a prime opportunity to introduce and discuss the problems of credibility, experimental design, motives, and professional ethics.

Current events also offer timely investigations.

Quality television shows (such as NOVA) also offer glimpses into the human side of science. Teachers can help students delve beyond any immediate "ooh-aah" response (based on the science itself) to consider the nature of science as an enterprise.

Cautionary note: Many public presentations of science are overdramatized. Critical distance is warranted for accounts that

with TV shows to ensure they cover real science.

monumentalize heroes or try to draw "real lessons" from an idealized story. For cases to foster understanding of the nature of science (not just blind celebration of its achievements), they must be honest about flaws, missteps, and the human context of science.

Echoing the lesson periodically

Finally, as with any important theme, learning deepens with repeated exposure. One brief lesson devoted to the nature of science, especially with inexperienced students at the beginning of a school year, will hardly suffice. Rather, small lessons and comments introduced throughout the year help create more lasting understanding.

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http://www.mcps.umn.edu/members.html#FEL

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getinvolved links

International Society for the History, Philosophy, and Social Studies of Biology
Biologists collaborate with historians, philosophers, and sociologists in interdisciplinary study.
http://www.ishpssb.org/

The Skeptics Society
Promote critical thinking! (*Should one also think critically about skeptics?!*)
http://www.skeptic.com

Sample Black-Box Exercises
» http://www.depts.washington.edu/hssexec/committee/hss_nature.html
» http://www.weirdrichard.com/black.htm
» http://www.wested.org/werc/earthsystems/geology/magicbox.html

Sample Mock-Forensics Activities
» http://www.indiana.edu/~ensiweb/lessons/chec.lab.html
» http://www.indiana.edu/~ensiweb/lessons/crime.html
» http://www.accessexcellence.org/AE/ATG/data/released/0157-theasinclair/index.html

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Free online science fair projects, with complete instructions, for a variety of science classes, from astronomy to zoology, and for any grade level from K-12.
http://www.all-science-fair-projects.com/index.php

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3. About Charles Davenport: http://www.amphilsoc.org/library/guides/glass/davenpo.htm (accessed March 5, 2004)
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